Concept of Mechatronics Safety and Modularity Design for an Autonomous Mobile Soccer Robot

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Abstract—In this paper, we describe the concept, design and implementation of a series of autonomous mobile soccer robots, named “Musashi” robot, which have safety design which is based on ISO and a mechatronics modular architecture, to participate in the RoboCup middle-size league. In modularity design methodology, we show that the selection of a proper moving mechanism, a suitable vision system and a mechatronics modular architecture design can lead to realize a reliable, simple, and low cost robot comparing with most of car-like robots including many kinds of sensors and a complex design structure.

Keywords: Entertainment robotics, Mechanism design, Wheeled robot

I. INTRODUCTION

ROBOCUP is an international joint project to promote Artificial Intelligent (AI), robotics, and related field. It is an attempt to foster AI and Intelligent robotics research by providing standard problems where a wide variety of technologies can be integrated and examined. In RoboCup, soccer game is selected as a main topic of research, aiming at innovations to be applied for socially significant problems and industries in the future [1]. “Hibikino-Musashi” is a joint RoboCup middle-size league soccer team[2,3]. Members of the team are from three different research and educational organizations located in the Kitakyushu Science and Research Park, Kitakyushu, Japan. In this paper, a design methodology to realize a safety, simple, robust, and mobile platform for Musashi robots is presented. Musashi robots are a series of autonomous mobile soccer robots which have a modular architecture in their hardware. This robot includes an omni-directional moving mechanism, an omni-vision and a novel ball-kicking device, and is developed as a reliable and robust soccer robot with high degree of simplicity, mobility, and maneuverability. This paper presents the details on the current state of hardware architectures.

II. CONCEPT OF DESIGN

Figure 1 shows the first version of our robot, which is purchased from “Frounforer AIS (Institute Autonomous Intelligent System)” [9]. This robot has a car-like locomotion mechanism including two active wheels and two castor wheels in the back and front, respectively. A digital camera with a 70 [deg] wide-angle lens is mounted on the top of the robot. The camera is controlled by a DC motor and an absolute encoder to have 360 [deg] rotation in the horizontal plane. As the robot moves in a dynamic environment avoiding obstacles, the robot is also equipped with different kinds of sensors such as two IR sensors, two distance sensors, and touch sensors. A pneumatic kicker whose air is supplied by two small air pressure tanks is installed on the robot.

With regard to the mechatronics design mentioned above, the existing problems can be itemized as follows:

(a) Poor mobility functions to perform the requested motion such as rotation around the ball or lateral movements.
(b) Complex data processing caused by many kinds of sensors.
(c) Complexity of the camera motion control including designing hardware and software.
(d) Design is not compatible and safe to have interaction with human.
(e) Low reliability and not enough robust for dynamic environments such as RoboCup.
(f) Complex mechatronics system in consideration from the viewpoints of assembling, maintenance, extendibility, troubleshooting, and transportation.
(g) Low speed ball kick, comparing with the other team’s robots which can shoot the ball in high speed up to 6.0 [m/s][4,5].

Fig.1 The first robot of “Hibikino-Musashi” team equipped with 11 sensors

1The three organizations are: Kyushu Institute of Technology, The University of Kitakyushu, and Kitakyushu Foundation for the Advancement of Industry Science and Technology.
In order to solve problems mentioned above and to achieve the required characteristics for the RoboCup scenario, a new mobile robot named “Musashi” is designed, and constructed for “Hibikino-Musashi” team. In this design approach, we show that selection of a proper moving mechanism, a suitable vision system and mechatronics modular architecture design can lead to realize a reliable, simple, and low cost robot comparing with the previous car-like robot with many kinds of sensors and a complex design structure in its hardware and software.

III. “MUSASHI” ROBOT ARCHITECTURE

Musashi robot is designed based on two significant and fundamental concepts: “omni-directional” and “modularity” concepts [6].

A. “Omni-directional” Concept

Musashi robot is an omni-directional mobile platform with an omni-vision (Fig. 2). The dynamical and kinematics characteristics of the omni-directional design allow for a high maneuverability in the field. The 3D mechanical structure is designed with 3D CAD Autodesk Inventor and the mechanical parts are manufactured by “Hibikino-Musashi” team members. Each robot is equipped with 3 omni-wheels, each of them driven by a 90 [W] DC motor. Gearboxes with reduction ratios of 12:1 are used to reduce the high angular speeds of the motors (7000 rpm) and to amplify the wheels torque.

The rotation velocity of a wheel is fed back to the motor driver using 540 [ppr] digital incremental encoders. The velocities of three wheels are controlled by three Faulhaber motor drivers (MCBL 2805) where each one has a RS232 communication port. The robot can move with maximum speed of 3.4 [m/s] and acceleration of 2.5 [m/s²]. In this approach, we could figure out the first problem (a) mentioned in the previous section.

The problems (b) and (c) are solved by changing the mono-directional vision (the vision system of the first version of our robot) to the omni-directional vision system which consists of a digital camera (IEEE 1394) and a hyper-bolic mirror. The main parameters, the height of the mirror (H) and distance between mirror and the camera (h) shown in Fig. 2, are determined so that the invisible area of the omni-vision camera is almost the same with the robot occupation shape [8]. The omni-vision can be used for not only object detection and localization, but also collision avoidance in spite that our first robots need the different types of sensors to avoid the contact with the other robots.

Table 1 shows the specification of “Musashi” robot. As shown in Table 1, the sensors used in “Musashi” robot are an omni-directional camera and three DC motor encoders, whereas the first version of our robot is equipped with 11 sensors (two IR sensors, two distance sensors, a camera, two DC motor encoders, touch sensors, two limit switches for robot fingers, and an absolute encoder for camera motion). Figure 3 shows the flowchart of Musashi robot power system including a main Li-Polymer battery (25.9 [V]) and an extra Li-Polymer battery (7.2 [V]) for high acceleration and speed during catching and carrying a ball. The necessary voltage for the camera and the micro computer power supply are converted from 25.9 [V] to 12.0 [V] and 5.0 [V], respectively. The power consumption of the robot is approximately 40 [W] and the operation estimated duration of the robot is 0.5 [h].
B. “Safety” Concept

This section describes the safety strategy. Recently, many robots such as industrial and service robots are being developed. Industrial robots are mostly manipulators having a necessary number of degrees of freedom. When the controller fails operation, the robot can possibly harm the human operator. The International Organization of Standardization (ISO) provides principles of machine design in general, by ISO 12100[11]. Additionally, ISO10218 standard [10], based on ISO12100, defines principal of design for industrial robots for keeping the operator safe. The engineers should reduce the risk based on principle of safe design, so that they should satisfy the demands from society. That is to say, a service robot can be accepted and used in society, if the designers of the robot can satisfy the principle of safe design. In the RoboCup soccer, there is a direct interaction between robots and humans that it might cause severe of injury for people who working and operating the robots. Therefore, as one of principles of safe design, we should consider the safety problem of the robot that is used in RoboCup Soccer as well.

One of RoboCup’s final goals is to win against the human World Cup Champion team. However, at present there are no rules about safety in RoboCup Soccer Middle Size League. It is important to keep the human safe when the robot crash into a human. We did a risk-assessment referring to the ISO14121 [12][13] where it is written in details about the risk-assessment to make the robots safe. Safety which refers to the ISO is stable robot design and reduces the risks, dramatically. As an example, Table 2 introduces the high risk of “Musashi” robot.

Risk assessment method is needed to avoid the risk not accepted by the ISO12100. ISO12100 shows how to decrease the risk by “3step-method”. Here we introduce the way to reduce the risk that is considered as high risk in “Musashi” robots.

First step: this is intrinsic safe design. This is the way which shows how to reduce the risks like dangerous space and sharp parts by intrinsic safe design. However, a lot of robots that are used in RoboCup have already been built. Therefore, it is difficult to reduce the dangerous points by design. Therefore, we need to increase safety by the next step.

Second step: this step is safeguarding and added guard. It is possible to say that adding an emergency switch is a common way to add safety to each hazard. If in the robot something breaks and when there are people in the game field, the robot should be stopped immediately. Therefore, putting an emergency switch on is effective. However, there remains the risk of breakdown of the emergency switch. This risk is passed to the referee and the participants.

Third step: this step is providing information to users. Actually, the risk which cannot be satisfied by first and second steps can be considered as information or instructions to inform the participants who enter the field by each team’s members. For example, referee and participants put on shoes when they enter the field.

Now, referee is only person who has the highest risk of injuring by the robot during the game in the robot soccer field. Therefore, if referee keep with safety guaranteed, the risk of the accident can be reduced dramatically. In fact, in the case of industrial robot, the safety of workers and operators can be guaranteed by fencing around the robot work space, and take attention of “NO ENTER” sign to the fence when ther robot is working. However, in RoboCup MSL case, it is impossible to fence the robots and keep referee far from the robots moving area. In fact, the referee is necessary to have a direct interaction with robots during the game same as real soccer (change the ball position, judging and so on). However, for making sure the risk, organizer should explain for referee and participants about specific of robot, expected mistake behavior and the result of risk assessment. After achieved the accountability, the designer of the robot can escape the responsibility. However, in the present RoboCup MSL rule aren’t written about the responsibility. Therefore, when some accident happens, no one can take responsibility. It is important for participants to clear the critical hazard and to implement the safety measure beforehand.

For the future of the RoboCup MSL, we should make the global safety standard. Then, it is important and necessary to count the safety in the process of the robot design in point of reducing of risks make the safe robots by design with considered safety. In our team, we try to reduce the risk and make safety robots considering the simple design and “Modularity” concept.

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Contents of hazards</th>
<th>Severe of an injury</th>
<th>Frequency</th>
<th>Evasion</th>
<th>Scale of risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run over by wheel mechanism</td>
<td>High</td>
<td>High</td>
<td>Possible</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Collides with human</td>
<td>High</td>
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<td>High</td>
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<tr>
<td></td>
<td>Touch of sharp parts</td>
<td>High</td>
<td>High</td>
<td>Possible</td>
<td>High</td>
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<tr>
<th>Safety strategy</th>
<th>Remained risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setting emergency switch, Put on the sensor</td>
<td>Breakdown of emergency switch and sensors</td>
</tr>
<tr>
<td>Put on the soft cover, Setting emergency switch</td>
<td>Break down of emergency switch</td>
</tr>
<tr>
<td>Remove the sharp parts, Setting emergency switch, Put on the sensors</td>
<td>Breakdown of emergency switch and sensors</td>
</tr>
</tbody>
</table>

**TABLE II**

RESULT OF RISK ASSESSMENT

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Crush</th>
<th>Shock</th>
<th>Rub, Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents of hazards</td>
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<td>Collides with human</td>
<td>Touch of sharp parts</td>
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</tr>
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C. “Modularity” Concept

First step: Description of the Robot System Architecture

To describe and emphasize the “modularity” concept, it is necessary to have a short overview of the robot system architecture design. Musashi robot is equipped with a laptop on which the image processing, control, communication and data exchange are performed. The behavior commands such as start, stop, corner kick, etc, are received from a referee box PC located outside of the field via on-board wireless LAN. To achieve a safe, simple, and robust system, the samplings of sensor data and actuator control are executed using conventional interfaces: IEEE 1394, USB, and RS232. The communication between an omni-directional camera and a mounted laptop PC is performed using IEEE 1394 interface. The laptop PC sends the motor control commands (target velocity) to the motor drivers via USB interface and USB/serial converters because a motor driver has only a RS232 serial port (Fig.4). Another USB/RS232 converter is used for communication between the laptop PC and the circuit of kicking device.

Second step: Defining the possible modules (single module)

Based on the flowchart of the robot architecture (Fig.4), the possible modules should be defined by considering the similar hardware structures or similar mechanical connections. Figure 4 shows the six possible modules illustrated with six different colors for “Musashi” robot hardware. For examples, an USB hub and four USB/RS232 converters can be a module (USB module) because they have a common interface. Another consideration is the mechanical similarity such as an omni-wheel and a motor (MW modules). One of the significant considerations in the process of a single module design is that: Each module should be designed to have a mechanical interface capable of attaching to the back plane “directly”. The mechanical interface should be fixed to the module except for special cases such that fixing the connector is not possible or the complex design and expensive manufacturing are required. Figure 5 show a developed motor driver module (MD module) and an USB module.

Third step: Merging the single modules (merged module)

The “modularity” concept can be extended by merging the single modules into a “merged modules” aiming at the
IV. STRONG NOVEL KICKING DEVICE

In 1997, RoboCup middle size league robots had no kicking device. One year later (the second RoboCup game, 1998), Freiburg team had made the first kicking device in the history of the RoboCup and became the champion [5]. After 1998, developing kicking devices became a key point for all participating teams.

A new kicking device for Musashi robots is designed using torsion springs, based on two following main functions.
(a) Function to shoot the ball with high speed (target velocity is up to 5.0 or 6.0 [m/s])
(b) Function to lift the ball (target height is above 1.0 [m]).

In general three mechanisms are necessary to use energy of a spring: At first, a mechanism for charging a spring (saving energy). Second, a mechanism to lock the spring (keeping energy). And then, a mechanism to release the spring (releasing energy). In the developed novel kicking device presented in this section, we designed a mechanism instead of these three mechanisms which saves, keeps and releases the energy of a series of torsion springs just using a motor and control using a limit switch. At first, a cam mechanism is used to charge the torsion springs and save the energy. The basic concept of this mechanism is shown in Fig. 8. With regard to the eqs. (1) and (2), the motive force \( F \) to charge the torsion spring is minimized while the force \( F \) is perpendicular to the \( m \) axes (\( \beta = 90 \) [deg]) in the condition that the torque \( \tau_S \) and \( X \) take certain values.

\[
\begin{align*}
F_x(\beta) &= \tau_S / (X \cdot \sin \beta) \\
F_{\min} &= F(90') = \tau_S / X
\end{align*}
\]

\( F_{\min} \) and \( \beta \) are the main function of the special designed cam is keeping the angle \( \beta \) equal to 90 [deg] during the spring charging process (see Fig. 9). The torque of a motor \( \tau_C \), needed to charge the spring, will be minimized as following equation:

\[
\tau_{C(\min)} = F_{\min} \cdot d
\]

Where \( d \) is the distance between the direction of contact force \( F \) (line \( N \)) and the center of the cam \( C \). The distance \( d \) can be calculated with the following equations:

\[
\begin{align*}
\text{Line} N: & \quad y = x \cdot \tan \theta \\
\text{Line} M: & \quad x \cdot \cos \theta + y \cdot \sin \theta + l_1 = 0 \\
d &= \frac{-l_1 \cos \theta - l_2 \sin \theta + l_1}{\sqrt{\cos^2 \theta + \sin^2 \theta}}
\end{align*}
\]

Here, \( l_1 \) is the length of OG, and the angle \( \theta \) is the angle between the line OG and the line \( M \). The force \( F \) and \( \tau_C \) can be obtained as following equations:

\[
\begin{align*}
\tau_C &= F \cdot d = nk\alpha(1 - \cos \theta - l_2 \sin \theta / l_1) \\
F &= \tau_C / l_1 = nk\alpha / l_1
\end{align*}
\]

Where \( n \) is the number of springs, \( k \) is the stiffness coefficient of springs and \( \alpha \) is the charging angle of springs. In this mechanism, during the charging time, the perpendicular distance between the direction of contact force \( F \) and the center of the cam (d in Fig. 9) decreases when the spring torque \( \tau_C \) and the contact force \( F \) increase.

The red line in Fig. 10 shows the derivation of motor torque relative to the charged angle of springs. The important point is that more the spring is charged, less the required motor torque is getting in the second half of the graph in Fig. 10.
Fig.10 The derivation of motor torque (\(\tau_m\)) (blue line) and spring torque (orange line) respect to the charged angle of spring \(\alpha\) where \(n = 2, k = 3.0 \text{[Nm/deg]}, \alpha = \text{maximum 22 [deg]}, l = 50 \text{[mm]}, j = 50\text{[mm]}\).

Fig.11 The sequence of charging of spring in beginning, middle, and end of the charging process. In the end of the process of charging because of the direction of force \(F\) passes the center of the cam, the mechanism has inherent characteristics to lock
due to the inherent characteristics to lock any motor torque as shown in Fig.11. It is clear that when the motor continues to rotate after the locking process, the spring will be released rapidly.

VI. CONCLUSION

In this paper, we described the concept, design and implementation of a series of autonomous mobile soccer robots, named “Musashi” robots. Musashi robots are designed based on three significant and fundamental concepts: “omni-directional”, “safety” and “modularity” concepts. With regard to the first concept, an omni-directional mobile platform whereas designed as “Musashi” robot to extend its maneuverability and performance comparing to traditional car-like robots platform limited by the poor kinematics and dynamics motions. Also, we selected an omni-directional vision system consists of a digital camera (IEEE 1394) and a hyperbolic mirror, which are mounted on the top of the robot. In this approach, the omni-camera can be used for not only object detection and localization but also collision avoidance. While previous robots need the different types of sensors and hardware to avoid the contact with the other robots and objects. As a result of omni-directional concept, Musashi robot can be operated using a sensor system by means of an omni-directional camera and three DC motor encoders with the minimum setting, in spite that the first version of our car-like robot is equipped with 11 sensors.

Second concept, we proposed the mechatronics “safety” concepts which refer to the ISO. And, we did a risk-assessment referring to the ISO14121 where it is written in details about the risk-assessment to make the robots safe. For the future of the RoboCup MSL, we should make the global safety standard. Then, it is important and necessary to count the safety in the process of the robot design in point of reducing of risks make the safe robots by design with considered safety. In our team, we try to reduce the risk and make safety robots considering the simple design and “Modularity concept.”

As another concept, we proposed the mechatronics “modularity” concept which consists of three steps, starting with description of the robot system architecture, defining the single modules and finally merging the module. As for “Musashi” robot modular architecture, we designed and divided the robot into two main modules, Bottom module and Upper module. Consequently, Bottom module consists of six “single” modules and one “merged” module. In this approach we could realize a simple, reliable, robust, capable troubleshooting, and low cost robot.

In addition, we explained the design and developing process of a strong kicking device with capability of shooting (up to 5.0 [m/sec]) and lifting (up to 120 [cm]). The ball-kicking device is accomplished by designing an unique spring charging mechanism called “Cam Charger”. The key idea is to charge a series of strong torsion spring by using a special cam. One of the specific features of the Cam Charger mechanism is that, charging, keeping and releasing of the springs energy are realized by only employing a simple DC motor-gearhead and control using a limit switch. Employing the developed “Musashi” robots, “Hibikino-Musashi” team could get the 1st place at RoboCup Japan Open 2008 and was ranked among the best 8 teams at the RoboCup 2006 world championships in Bremen and 4th place at the RoboCup 2007 world champion ship in Atlanta.

REFERENCES

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